Upper Ocean Stratification in the Bay of Bengal

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LONG-TERM GOALS

In collaboration with Indian oceanographers, we seek to measure and understand the processes controlling the stratification of the upper 100m of the Bay of Bengal and to educate a new generation of young Indian oceanographers in the methods used.

OBJECTIVES

Upper ocean physics plays a key role in controlling the intensity and timing of the Northern Indian Ocean monsoons, with the ocean and atmosphere representing a strongly coupled air-sea interaction system, which in turn plays an important role in climate variability at both regional and global scales. The ASIRI program, a Departmental Research Initiative of ONR's code 32, seeks to understand these interactions through measurement and modeling focused on the Bay of Bengal. Existing coupled ocean-atmosphere models in this region show little skill in predicting the summer monsoon, particularly its IntraSeasonal Oscillations (ISO). One possible cause is a poor simulation of the air-sea interaction processes. The northern Bay of Bengal has strong ISO fluctuations in SST, which lead the monsoonal fluctuations by about a week, thereby suggesting a causal relationship between monsoon ISO variations and ocean dynamics. However, most existing models predict surface temperatures that are too cold and mixed layer depths that are too deep. The biases are large and likely reduce the intensity of air-sea interaction by overestimating the thermal inertia of the upper ocean and thus the time scale on which the ocean can respond to the atmosphere. A likely reason for this bias is an improper representation of the role of freshwater input, both from rain and from the enormous river inflow into the northern Bay of Bengal. Specific goals for this grant are:

- Measure the salinity and temperature stratification of the upper 100m with a particular emphasis on the upper 10m and mixed layer, if any, throughout the annual cycle including the summer monsoon and the ocean response to it and recovery from it.
- Understand the relative importance of vertical processes, as represented by wind, flux and wave driven boundary layer models, internal wave mixing, and lateral processes, as represented by submesoscale-resolving process models, in setting the stratification and upper ocean circulation.
- Collaborate with Indian oceanographers through the Ministry of Earth Sciences' monsoon mission program (OMM), ASIRI's partner in the Bay of Bengal studies. This is done by

participating in cruises on Indian research vessels, teaching at ASIRI/OMM workshops and working with Indian researchers and their students.

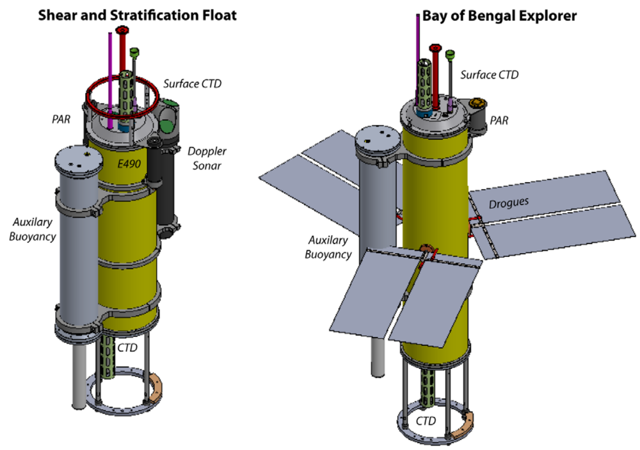

Fig. 1. The two ASIRI floats. Both include a second buoyancy unit allowing them to traverse the very strong stratification of the Bay of Bengal.

APPROACH

Since the early 1990s, ONR has supported the development and use of 'Lagrangian Floats" designed, built and operated at the Applied Physics Laboratory, University of Washington. These are robust platforms for studying upper ocean processes, capable of carrying a wide variety of sensor suites (we have integrated about 30 different sensors) and particularly designed to accurately track water parcels in three-dimensions. They are fully autonomous using Iridium communications for control and data transfer.

A particular challenge for all buoyancy driven vehicles (floats and gliders) in the Bay of Bengal is the presence of very fresh, low density water near the surface, which can prevent such vehicles from profiling all the way to the surface and/or lifting their satellite antennas far enough out of the water to communicate. Salinities as low as 21 psu, can occur here during and after the summer monsoon. Spanning the density range between this and the 100m depth, would require nearly all (~550cc) of the available (650cc) buoyancy control of a standard Lagrangian float.

Two Lagrangian floats have been constructed for the Bay of Bengal work. The Shear and Stratification Float is designed to be deployed from a ship and measure the near-surface shear and stratification in detail. The Bay of Bengal Explorer is designed for long-term (6+ months) operation, measuring stratification and turbulence. Systems on these floats are:

- 2 standard SBE-41CT ctd's, on the top and bottom of the float, measure salinity and temperature. Two sensors are needed given the strong density gradients to properly ballast the float and for redundancy since these are crucial sensors for float operation.
- A special Seabird 'Surface CTD' designed to rapidly profile the near-surface salinity as the float penetrates the surface on an upward profile. These sensors will provide very high vertical resolution near the surface where the Bay of Bengal stratification is very strong.

- Light sensors, designed to measure light level as a function of depth and thus the optical clarity of the water. This is crucial for determining the heating of the upper layer. The BBE has PAR sensor equipped with a window-wiper that actively removes fouling of the optical window. In previous deployments, we have found this to be very effective. The SSF has both a PAR and a 490 nm sensor in order to provide a more detailed view of the light field.
- A new auxiliary buoyancy module attached to the side of the float. This doubles the buoyancy control of the float by duplicating the current internal buoyancy system and thus allows the float to easily overcome the large salinity variations in the Bay of Bengal.
- The usual pressure sensors, Iridium communications, ARGOS backup system and software controlling a customized ASIRI float mission. The typical mission will alternate profiles to the surface with extended drifts of the float within the surface boundary layer to measure the turbulence levels and surface waves.

WORK COMPLETED

Eric D'Asaro and Michael Ohmart (the technician who builds the floats) participated in a cruise on the *R.V. Sagar Nidhi,* in August/September 2015, continuing joint work begun on cruises in November/December 2013 and August/September 2014. In the Indian *Sagar Nidhi* and *U.S. R/V Revelle* worked together to map a frontal region in the central Bay of Bengal. As in previous years, D'Asaro and Ohmart were the U.S. participants on the *Sagar Nidhi* and acted as coordinators with the *Revelle*. A Seaglider and the Stratification float (Fig. 2) were launched with our supervision. The float was recovered after 8 days; the Seaglider is still operating.

Eric D'Asaro lectured at the Indian space agency (ISRO/SAC) in December 2014 and participated in ASIRI/OMM meetings near Chennai (December 2014) and in Massachusetts (May 2015).

Fig. 2. Lagrangian float and Seaglider on the Sagar Nidhi before deployment.

RESULTS

Indian collaborations and training - The 2015 *Sagar Nidhi* cruise was highly sucessful. Approximately 4000 underway CTD (uCTD) profiles were taken along the cruise track. A 300 kHz ADCP installed on the *Sagar Nidhi* worked very well. A second 500 kHz ADCP, capable of shallower measurements, was installed on a side-pole and also worked well. These operations were conducted almost entirely by the Indian scientists trained on the 2013 and 2014 *Sagar Nidhi* and *R/V Revelle* cruises. None of this was possible during the 2013 cruise; progress in the last 2 years is remarkable and a direct result of our participation.

The collaborative work with R/V *Revelle* also worked very well, in marked contrast to similar efforts in 2013. The two ships ran parallel lines 2-4 km apart for 500 km to study the small-scale vorticity field. The *Revelle* then surveyed within 10 km around a drifting buoy placed in a salinity front, while *Nidhi* made an adaptive survey on 20-40 km scale. This required continual adjustment of the ship's track based on the uCTD and ADCP profiles, the first attempt to undertake adaptive sampling. This was done for 3 days by the Indian scientists, with only minor advice from D'Asaro. This is significant step forward in training young Indian oceanographers in modern techniques.

Individual training has also been proceeding. Two Indian scientists have been trained in float operations. They will deploy the Explorer float on a May 2016 cruise without our supervision, again raising the bar for training and independence. Dr. Praveen Kumar, one of the two, will visit APL/UW late in 2015 for additional training and to work on the 2015 Stratification float data. D'Asaro is working closely with two graduate students supervised by Prof. Debasis Sengupta at the Indian Institute of Sciences Bangalore. Their Ph.D. thesis will focus on the ASIRI/OMM data from the Bay of Bengal.

Our logistical operations have also improved somewhat from previous years. Both floats and our equipment were sucessfully shipped to the *Sagar Nidhi* within a few weeks, unlike in 2013 when they didn't make it to the ship at all. The paperwork for Foreigner Registration and transit of the port were also faster than in previous years.

Preliminary Float Results – The Stratification float was deployed for 7 days in a developing frontal zone defined by an array of salinity drifters deployed from the *Revelle*. The float profiled approximately every 3.5 hours, drifting on an isopycnal near 18m between drifts while profiling the velocity structure of the overlying mixing layer with an ADCP. Since the drift depth is very close to the drogue depth of the salinity drifters, the float stayed with the salinity drifters throughout its deployment. These, along with a nearby WireWalker, form a detailed coherent array mapping the three-dimensional evolving structure of the frontal zone in a Lagrangian frame.

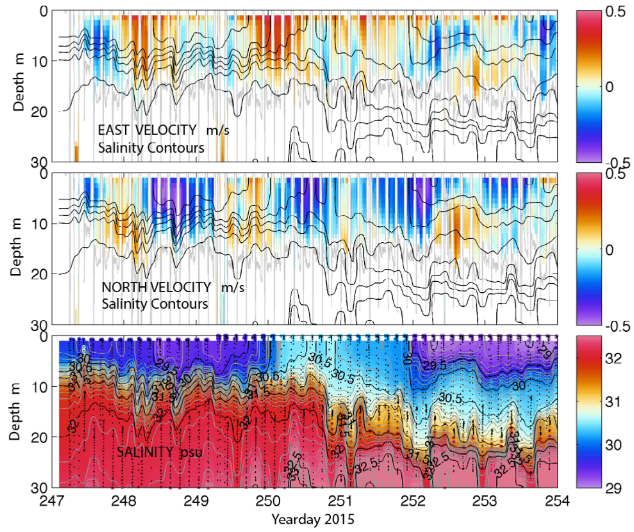

Figure 3. Data from the Lagrangian float deployment. a) East component b) North component c) Salinity.

All sensors on the float worked well, including the optics, surface CTD, regular CTDs and the ADCP. Comparison of the vertical velocity measured by the ADCP and the actual vertical motion of the float confirm that the ADCP was working well. Fig. 3 shows the velocity (Fig. 3ab) and salinity/density (Fig. 3c) structure of the boundary layer. The velocity is dominated by inertial oscillations in the mixed layer, which result in a strong shear between the mixed layer and the interior. Since the float mostly follows water below the mixed layer, the mixed layer salinity changes with time as the float moves beneath it, as clearly seen in Fig. 3c. These changes mirror those measured by the salinity drifter array and the ship surveys. The combined array shows that these changes are due to the float and drifters crossing a set of fronts and filaments. We expect that the more detailed analysis of these data will provide a detailed view of these features and their role in stratifying the Bay of Bengal.

RELATED PROJECTS

The ADCP/float measurements pioneered here are expected to play an important role in upcoming measurements as part of the Waves, Langmuir Cells and the Upper Ocean Boundary Layer Departmental Research Initiative